CHICAGO JOURNALS

Plate Tectonics and Geochemical Composition of Sandstones
Author(s): Mukul R. Bhatia
Reviewed work(s):
Source: *The Journal of Geology*, Vol. 91, No. 6 (Nov., 1983), pp. 611-627
Published by: The University of Chicago Press
Stable URL: http://www.jstor.org/stable/30064711
Accessed: 26/10/2012 10:54

Your use of the JSTOR archive indicates your acceptance of the Terms & Conditions of Use, available at
http://www.jstor.org/page/info/about/policies/terms.jsp

JSTOR is a not-for-profit service that helps scholars, researchers, and students discover, use, and build upon a wide range of content in a trusted digital archive. We use information technology and tools to increase productivity and facilitate new forms of scholarship. For more information about JSTOR, please contact support@jstor.org.

The University of Chicago Press is collaborating with JSTOR to digitize, preserve and extend access to *The Journal of Geology.*

http://www.jstor.org

VOLUME 91 NUMBER 6

THE JOURNAL OF GEOLOGY

November 1983

PLATE TECTONICS AND GEOCHEMICAL COMPOSITION OF SANDSTONES[1]

MUKUL R. BHATIA[2]
Department of Geology, Australian National University, Canberra A.C.T. 2600 Australia

ABSTRACT

Sandstones of the Paleozoic turbidite sequences of eastern Australia show a large variation in their major element geochemistry, reflecting the distinct sedimentary provenance and tectonic setting of each suite. On the basis of bulk composition, five suites are discriminated: Tamworth, Hill End, Hodgkinson, Bendigo, and Cookman. A close correlation exists between the geochemical composition of sandstones and tectonic settings of sedimentary basins. The nature of the continental margin and oceanic basins can be deciphered on the basis of the major element composition of sandstones. The most discriminating parameters are Fe_2O_3 + MgO%, TiO_2%, Al_2O_3/SiO_2, K_2O/Na_2O and $Al_2O_3/(CaO + Na_2O)$. In general, there is a progressive decrease in Fe_2O_3 + MgO, TiO_2, Al_2O_3/SiO_2, and an increase in K_2O/Na_2O and $Al_2O_3/(CaO + Na_2O)$ in sandstones from oceanic island arc to continental island arc to active continental margins to passive margins. Oceanic island arc sandstones are characterized by the high abundance of Fe_2O_3 + MgO (8–14%), TiO_2 (0.8–1.4%), and low Al_2O_3/SiO_2 (0.24–0.33) and K_2O/Na_2O (0.2–0.4) ratios. The continental island arc type sandstones can be distinguished from the oceanic island arc type by their lower Fe_2O_3 + MgO (5–8%) and TiO_2 (0.5–0.7%), and higher Al_2O_3/SiO_2 (0.15–0.22) and K_2O/Na_2O (0.4–0.8). The active continental margin type sandstones are characterized by low Fe_2O_3 + MgO (2–5%), TiO_2 (0.25–0.45%) and K_2O/Na_2O ratio $\simeq$ 1. Passive margin type sandstones are generally enriched in SiO_2 and depleted in Na_2O, CaO, and TiO_2, suggesting their highly recycled and matured nature.

INTRODUCTION

The geochemical composition of terrigenous sedimentary rocks is a function of the complex interplay of various variables, such as provenance, weathering, transportation, and diagenesis. Tectonism has been advocated as the primary control on sedimentary composition (Pettijohn et al. 1972, p. 237–244; Blatt et al. 1980, p. 732–738). Relationships between attributes of the plate tectonic setting (e.g., plate interaction, plate instability, burial depth, geothermal and pressure gradients) and variables such as provenance, relief, physical sorting, and diagenesis govern the composition of clastic sedimentary rocks (fig. 1).

Many recent studies have documented the relationship between the framework mineralogy of sandstones, provenance type, and the tectonic setting of sedimentary basins (Crook 1974; Schwab 1975; Dickinson and Suczek 1979). Modern sands of known tectonic settings also exhibit systematic variations in framework mineralogy as a function of provenance type and tectonic setting (Potter 1978; Dickinson and Valloni 1980; Valloni and Maynard 1981). Thus, the composition of sedimentary rocks is useful for recognizing the nature of ancient continental margins and oceanic basins.

The relationship between tectonic setting and sandstone composition is mainly based on framework modes. However, framework grains may not always reflect the true crustal

[1] Manuscript received January 18, 1983; revised June 14, 1983.

[2] Present Address: Australian Aquitaine Petroleum Pty. Ltd., P.O. Box 725, North Sydney N.S.W. 2060 Australia.

[JOURNAL OF GEOLOGY, 1983, vol. 91, p. 611–627]
© 1983 by The University of Chicago. All rights reserved.
0022-1376/83/9106-002$1.00

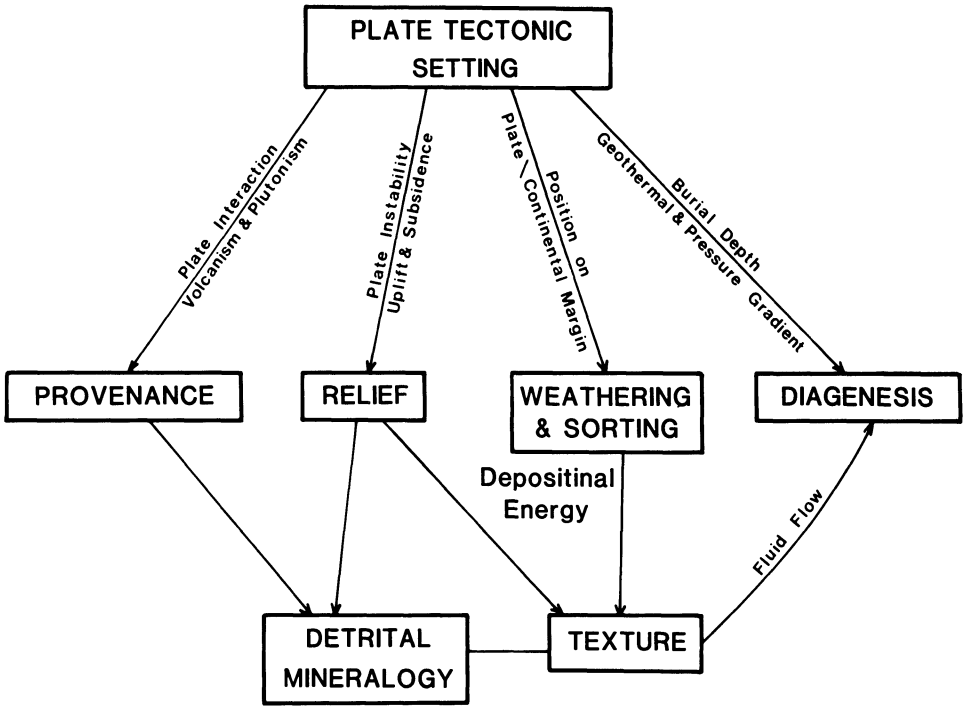

FIG. 1.—Relationships between attributes of the plate tectonic setting and compositional variables of sandstones.

setting. Andesitic detrital grains can be derived from arcs developed on widely different settings (e.g., intra-oceanic, partially continental, or continental margin). Moreover, the nature of grains could be obliterated or destroyed by post-depositional modifications. A large part of the matrix, especially in older sandstones of orogenic terrains, may have formed due to the degradation of lithic grains (Cummins 1962; Hawkins and Whetten 1969). Also, framework grains are almost impossible to identify correctly in sandstones which have been metamorphosed.

Thus, it is essential that the geochemical characteristics of various modern and ancient sandstone suites be understood in order to identify signatures of source rocks and tectonic settings in their compositions, and to infer the redistribution of elements during and after deposition. Geochemical criteria of tectonic setting discrimination have largely remained neglected, though it has been suggested that various sandstone types can be distinguished on the basis of the SiO_2 content and K_2O/Na_2O ratio (Middleton 1960; Crook 1974; Schwab 1975). Maynard et al. (1982) carried out major element determinations on modern deep sea turbidite sands and suggested that sands from fore-arc basins and the passive margins are distinct, but that sands from other settings cannot be separated on the basis of bulk composition.

The purpose of the present communication is to report some characteristics of the composition of Paleozoic turbidite sandstones of eastern Australia and to propose major element geochemical criteria to discriminate plate tectonic settings of sedimentary basins on the basis of these well defined sandstone suites and other published analyses of modern and ancient sands.

CLASSIFICATION OF SEDIMENTARY BASINS

In geosynclinal terminology, basins are classified into two major (miogeosynclinal and eugeosynclinal belts) and several minor types (Kay 1951). However, a direct correspondence between the plate tectonic setting of modern basins and geosynclinal terminology was found to be elusive (Mitchell and Reading 1969; Dickinson 1974). The first order classification of continental margins into active (or leading) and passive (or trailing) does not describe adequately the variation in

the sedimentary basin type. A purely geomorphic classification of sedimentary basins is also unsatisfactory as similar geomorphic basins can occur in different tectonic settings, e.g., a fore-arc basin can be completely oceanic, partially oceanic, or can develop on a continental margin (Dickinson and Seely 1979).

A simplified plate tectonic classification of continental margins and oceanic basins based on the nature of the crust has been followed, (see Bhatia and Crook 1983 for details) and four types recognized.

1. Oceanic Island Arc.—Sedimentary basins adjacent to the oceanic island arcs (e.g., Marianas) or island arcs partly formed on thin continental crust (e.g., Aleutians). These have been called "migratory" and "stationary" arcs, respectively, by Dickinson and Seely (1979). In this tectonic setting, a volcanic arc separates the fore-arc from an oceanic back-arc basin. Sediments are mainly derived from the calc-alkaline or tholeiitic arc.

2. Continental Island Arc.—Sedimentary basins adjacent to island arcs formed on a well-developed continental crust (e.g., Lau Basin; Japan Sea) or on thin continental margins (e.g., Cascades-Western ,USA). These correspond to "detached" and "noncontracted" type arc-trench systems, respectively (Dickinson and Seely 1979). Arcs of this tectonic setting are continental fragments, detached from the mainland. Sediments are deposited in inter-arc, back-arc, and fore-arc basins and are mainly derived from felsic volcanic rocks. Back-arc basins formed on the continental side of the island arc (e.g., Sea of Japan) are included in this setting.

3. Active Continental Margins.—Include sedimentary basins of the Andean type thick continental margins (e.g., N. Chile, Peru) and the strike-slip types (e.g., Pacific Ocean off California). These basins are developed on or adjacent to a thick continental crust composed of rocks of older fold belts. Sediments are dominantly derived from granite-gneisses and siliceous volcanics of the uplifted basement. Sedimentation in the Andean type setting takes place in marginal and retro-arc basins.

4. Passive Margins.—Comprise rifted continental margins of the Atlantic type developed along the edges of the continents, remnant ocean basins adjacent to collision orogens, and inactive or extinct convergent margins. The sediments which are generally highly matured are derived by the recycling of older sedimentary and metamorphic rocks of platforms or recycled orogens. Intracratonic and rift-bounded grabens (e.g., Benue Trough) are formed on a thick continental crust and are included in the passive margin type tectonic setting.

METHODS AND PROCEDURES

Geochemical Techniques.—Sixty-nine samples representing five Paleozoic sandstone suites of eastern Australia were analyzed for major and trace elements using an automatic X-ray fluorescence spectrometer and following the method of Norrish and Hutton (1969). All analyses were carried out in triplicate. Na was determined on a modified Baird-Atomic double beam photometer with a propane-air flame, using Li as an internal standard (Cooper 1963). FeO was determined by titration method using the technique of Peck (1964). Ferric iron was calculated by the difference from the total iron content measured by X-ray fluorescence.

Statistical Methods.—Discriminant function analysis is a powerful technique in classifying individual cases (samples) into predefined groups on the basis of multiple variables. There are several examples of the application of this technique in solving geological problems (e.g., Davis 1973; Klovan and Billings 1967; Davies and Ethridge 1975; Le Maitre 1982). Discriminant functions for sandstone geochemistry were given by Middleton (1962) to distinguish the following tectonic settings: miogeosyncline, eugeosyncline, and taphrogeosyncline. Many of the analyses on which this study was based were incomplete, and the tectonic regimes have since been shown to be inadequate in describing the variation in basin types (Dickinson 1974).

The objective of this analysis is to get a discriminant function of the form

$$D_i = a_i x_1 + b_i x_2 + c_i x_3 + \ldots + p_i x_p \pm C \quad (1)$$

such that the pre-defined populations have maximum separation along the function. In

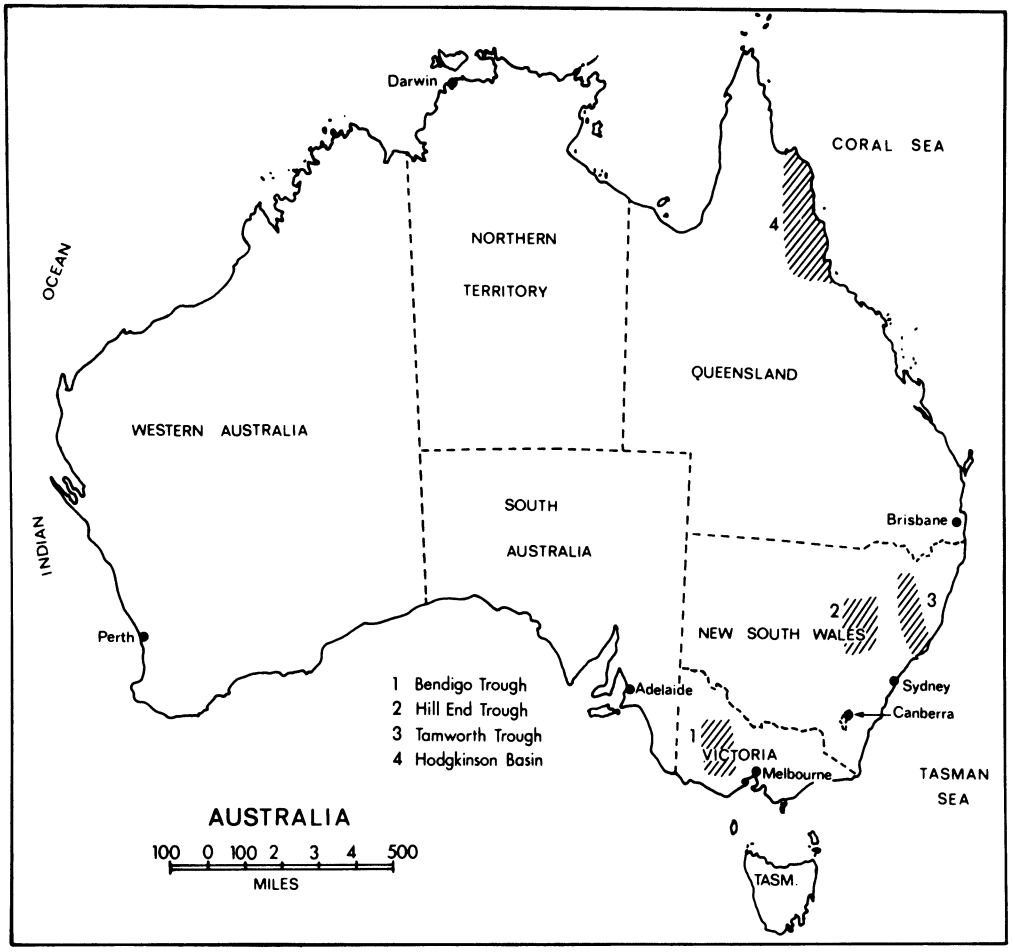

FIG. 2.—Location of sedimentary basins.

the equation given above, $x_1, x_2, x_3, \ldots, x_p$ are the p discriminating variables; a_i, b_i, c_i, $\ldots$, p_i are the discriminating function coefficients; D_i is the discriminant score, and C is a constant. The magnitude of the standardized discriminating coefficients associated with variables show the relative importance of the variables in separating the groups along the discriminant function.

The number of discriminant functions to be obtained is one less than either the number of groups or the number of variables, whichever is less. For each discriminant function, Wilks' lambda indicates the statistical significance, the canonical correlation coefficient signifies the strength of the function in discriminating, and the eigenvalue indicates the percentage of variation explained by the function in the original data (Cooley and Lohnes 1971). The computer programme DISCRIMINANT of the SPSS system (Nie et al. 1975) on UNIVAC 1100 was used to carry out the analysis.

PALEOZOIC SANDSTONE SUITES OF EASTERN AUSTRALIA

Geochemical Compositions.—The following five Paleozoic sandstone suites of the Tasman Geosyncline of eastern Australia (fig. 2), representing distinct source rocks, provenance types, and tectonic settings, were delineated on the basis of mineralogical and geochemical compositions: (1) Tamworth suite (Devonian); (2) Hill End suite (Silurian-Devonian) (including three samples of the Carboniferous Crow Mountain Creek Beds); (3) Hodgkinson suite (Devonian); (4) Bendigo suite (Ordovician); and (5) Cookman suite (Silurian). The sandstone suites are of the graywacke type, occurring in orogenic ter-

TABLE 1

AVERAGE MAJOR ELEMENT COMPOSITIONS OF PALEOZOIC SANDSTONE SUITES OF EASTERN AUSTRALIA

	Tamworth Suite	Hill End Suite	Hodgkinson Suite	Bendigo Suite	Cookman Suite
Samples	11	29	10	7	8
SiO_2	55.79	71.66	76.79	83.79	85.63
TiO_2	.81	.63	.44	.49	.27
Al_2O_3	15.37	11.80	10.82	7.36	7.85
Fe_2O_3	1.59	.99	.62	.55	.53
FeO	4.69	2.84	1.96	1.59	0.48
MnO	.22	.08	.05	.02	.01
MgO	2.57	1.43	.99	.98	.39
CaO	6.65	2.54	1.16	.18	.10
Na_2O	4.49	2.43	2.27	1.36	.89
K_2O	1.10	1.75	2.65	1.30	1.27
P_2O_5	.18	.12	.08	.13	.08
S	.36	.03	.04	.02	.02
H_2O^+	2.55	1.99	1.34	1.49	1.87
H_2O^-	.42	.12	.09	.14	.17
CO_2	2.88	1.28	.67	.48	.20
TOTAL	99.85	99.69	99.97	99.88	99.76

rains and were deposited by turbidity currents and mass-flow processes. The average major element composition of each suite is given in table 1, and the individual analyses are given in Bhatia (1981). A brief description of the geological setting of the sedimentary basins is given in Bhatia (1983), Bhatia and Taylor (1981), and Bhatia and Crook (1983).

Variations in the major element geochemistry of various sandstone suites are shown on Harker diagrams (fig. 3). In general, SiO_2 increases and TiO_2, Al_2O_3, FeO (total Fe as FeO), MnO, MgO, CaO, and Na_2O decrease from the Tamworth through the Hill End, Hodgkinson, Bendigo to Cookman suite sandstones due to the increase in mineralogical maturity. This mineralogical maturity is characterized by an increase in the quartzose content and a decrease in unstable detrital grains (e.g., feldspar and volcanic rock fragments) from the Tamworth ($Q_8F_{41}L_{51}$) through the Hill End ($Q_{54}F_{17}L_{28}$), Hodgkinson ($Q_{71}F_{18}L_{11}$), Bendigo ($Q_{94}F_3L_3$), to the Cookman ($Q_{87}F_1L_{12}$) suite sandstones. (The QFL represents the relative proportions of quartz, feldspar and rock fragments.) K_2O first increases from the Tamworth through Hill End to the Hodgkinson suite, due to the increase in the K-feldspar and mica content, and then decreases toward the highly matured feldspar depleted Bendigo and Cookman suites.

The provenance of these sandstone suites can be depicted on a CaO-Na_2O-K_2O ternary diagram on which the average compositions of andesite-dacite-granodiorite and granite (Le Maitre 1976) are also plotted (fig. 4). The sandstones of the Tamworth suite are characterized by low SiO_2 (~58%) and K_2O (~1.5%), and the highest total FeO, TiO_2, MgO, Na_2O, and CaO of all sandstone suites. Their composition is similar to that of the average andesite (fig. 4) but in general is slightly higher in Na_2O due to the albitisation of Ca-plagioclase.

The sandstones of the Hill End suite are lower in TiO_2, MgO, CaO, and Na_2O compared to the Tamworth suite and have a composition similar to that of the average dacite or granodiorite. The sandstones of the Hodgkinson suite are significantly richer in SiO_2 and K_2O and poorer in Na_2O and CaO compared to the sandstones of the Tamworth and Hill End suites (fig. 3). They plot around the average granite on the CaO-Na_2O-K_2O diagram (fig. 4) but are slightly lower in the absolute abundance of CaO and Na_2O due to a lower feldspar content. The Cookman suite samples are significantly enriched in SiO_2 and depleted in total FeO, MgO, CaO, and Na_2O

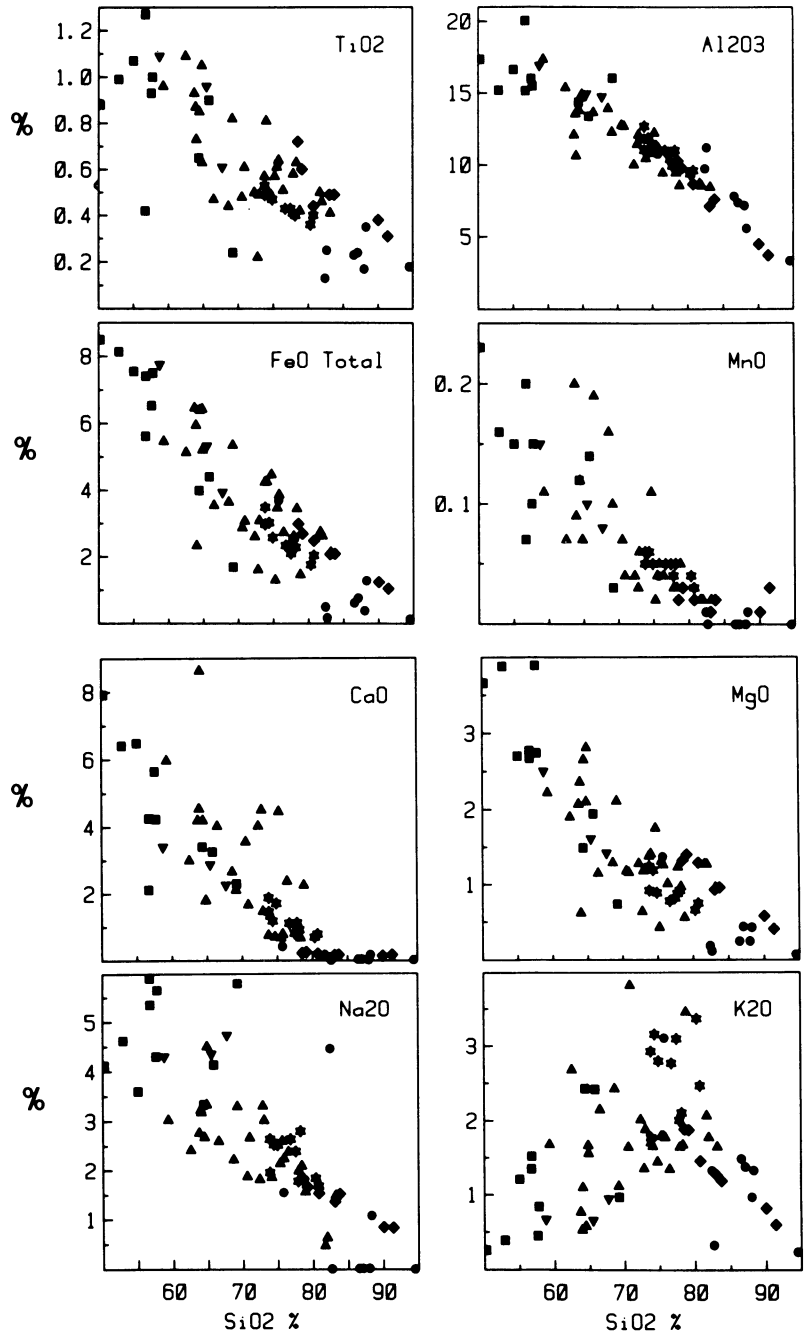

FIG. 3.—Harker Variation diagram of major elements for sandstone suites of eastern Australia. Symbols are: *square:* Tamworth suite; *inverted triangle:* Crow Mountain Creek Beds; *triangle:* Hill End suite; *star:* Hodgkinson suite; *hexagon:* Bendigo suite; *circle:* Cookman suite.

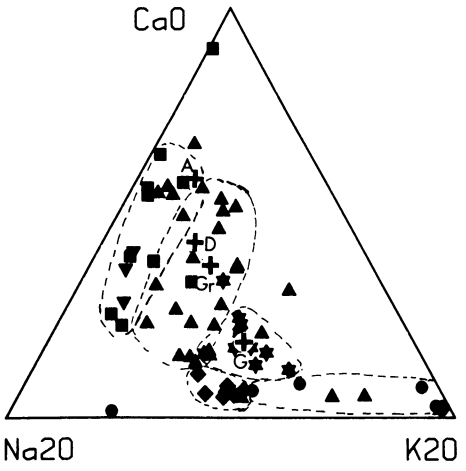

FIG. 4.—CaO-Na_2O-K_2O plot for sandstone suites of eastern Australia. Dotted lines mark the broad fields of various suites. Also plotted are the averages of andesite (A), dacite (D), granodiorite (Gr), and granite (G) after Le Maitre (1976). Symbols as in figure 3.

compared to all other suites (fig. 3). Their highly matured and recycled nature is reflected in their relative enrichment of K_2O and depletion of Na_2O and CaO compared to the average granite (fig. 4).

Discriminant Function Analysis.—Discriminant function analysis was performed using 11 major element oxides as variables and the five sandstone suites of eastern Australia as pre-defined groups. Discriminant Functions I and II together explain about 90% of the variation in the data, and the high canonical correlation coefficients and low Wilks' lambda values signify their high discriminating power (table 2). Functions III and IV explain only a small variation in the data.

Discriminating scores corresponding to first two functions for each sample were calculated following equation (1) given previously. In this calculation, $x_1, x_2, x_3, \ldots, x_p$ represent the actual abundance (in %) of the element oxides in the sample, and $a_i, b_i, c_i, \ldots, p_i$ represent the values of unstandardized discriminating coefficients (table 3). A plot of scores along Function I versus Function II differentiates between the various sandstone suites (fig. 5). Function I has a high loading of CaO and Na_2O and is mainly influenced by the plagioclase and volcanic fragments in sandstones. This function separates the highly feldspathic Tamworth suite from the less feldspathic Hill End suite. Function II is mainly influenced by SiO_2 and CaO and discriminates highly quartzose Bendigo-Cookman suites from the less quartzose and more feldspathic Hodgkinson suite. The close grouping of the Bendigo and Cookman suite samples indicates that the differences between these two suites are not very high and that the probability of misclassification is very large. The Bendigo suite samples have only a slightly higher loading of CaO and Na_2O along Function I, reflecting a slightly higher plagioclase content compared to the Cookman suite. On the basis of discriminant functions I and II, 81% of the samples are correctly classified into their pre-defined groups (table 4).

Tectonic Settings.—The Paleozoic sandstone suites of eastern Australia are assigned to various tectonic settings, using three sets of criteria: regional geology; comparison of the mineralogical data of sandstones with those of modern deep sea sands; and the comparison of trace and rare-earth element characteristics of sandstones, especially La, Ce, Th, Nb, La/Y, La/Sm, Hf/Yb, Ni/Co, and Sc/Ni, with those of modern andesites from various tectonic settings (Bhatia 1983; Bhatia and Crook 1983). The sandstones of the Tamworth and Hill End suites were deposited in fore-arc and apical inter-arc basins, respectively. They are assigned to oceanic and continental island arc settings, respectively, due to the similarities in their characteristics with those of andesites from these settings. The sandstones of the Hodgkinson suite have trace-element and mineralogical characteristics similar to andesites and deep-sea sands of the active and thick continental margins. The sandstones of the Bendigo and Cookman suites are highly quartzose and depleted in feldspar, similar to modern deep-sea sands from the passive margins (cf. Dickinson and Valloni 1980; Valloni and Maynard 1981). These suites were deposited in a marginal basin adjacent to a tectonic highland or in a passive margin type of setting.

GEOCHEMICAL CHARACTERISTICS AND TECTONIC SETTING DISCRIMINATION

Major elements undergo some changes during sedimentary processes, e.g., in most basins SiO_2 is enriched, and Na_2O and CaO are depleted in sandstones compared with the

TABLE 2

STANDARDIZED DISCRIMINANT FUNCTION COEFFICIENTS AND RELATED STATISTICS OF SANDSTONE SUITES OF EASTERN AUSTRALIA

	Discriminant Functions			
	I	II	III	IV
SiO_2	−.309	−2.910	1.166	−3.610
TiO_2	−.198	.405	.337	.628
Al_2O_3	.0167	−1.171	−.502	−1.767
Fe_2O_3	−.119	−.248	−1.011	.076
FeO	.257	−1.991	−.379	−.266
MnO	−.397	.351	.419	−2.542
MgO	.089	.558	1.444	−.622
CaO	.621	−2.894	.812	−.822
Na_2O	.642	−.158	.607	−.524
K_2O	−.022	−1.271	.606	−.186
P_2O_5	.441	.425	.465	−.235
Eigenvalue	3.42	1.17	.27	.19
% of Variation Explained	67.5	23.1	5.4	3.9
Cumulative Variance	67.5	90.6	96.0	99.9
Canonical Correction	.879	.735	.464	.407
Wilks' Lambda	.068	.301	.654	.834

source rock composition. Thus, the major element chemistry gives clues as to the provenance type as well as weathering conditions, both of which are controlled by the tectonic setting of the basin (fig. 1). Diagenesis also influences the bulk composition of sandstones, but the nature of diagenesis is itself dependent on the tectonic setting of the basin (Siever 1979).

Thirty averages of published sandstones and modern sands from various regions of the world are compared with the present data of the sandstone suites of eastern Australia and grouped into various tectonic settings (tables 5–8). No attempt was made to include all the available published analyses. However, averages of various sandstones, e.g., arkose, graywacke, lithic arenite, and quartz

TABLE 3

UNSTANDARDIZED DISCRIMINANT FUNCTION COEFFICIENTS USED TO CALCULATE DISCRIMINANT SCORES FOR SANDSTONES

	Discriminant Functions		
	I	II	III
SiO_2	−.0447	−.421	.169
TiO_2	−.972	1.988	1.657
Al_2O_3	.008	−.526	−.226
Fe_2O_3	−.267	−.551	−2.248
FeO	.208	−1.610	−.306
MnO	−3.082	2.720	3.258
MgO	.140	.881	2.281
CaO	.195	−.907	.254
Na_2O	.719	−.177	.681
K_2O	−.032	−1.840	.878
P_2O_5	7.510	7.244	7.913
Constant	.303	43.57	−15.87

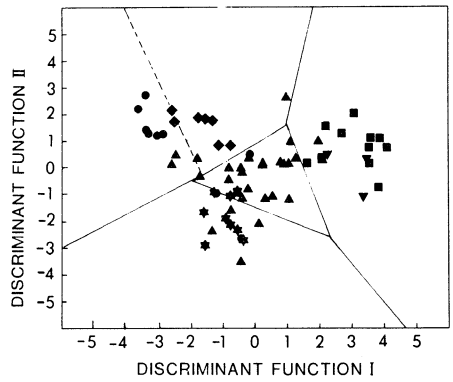

FIG. 5.—Plot of discriminant scores along Function I versus Function II, to discriminate various sandstone suites of eastern Australia. The continuous lines mark the major fields of various suites and are computer derived. The dotted line marks low discrimination. Symbols as in figure 3.

TABLE 4

COMPARISON BETWEEN ACTUAL AND PREDICTED NUMBER OF SAMPLES IN EACH SANDSTONE SUITE OF EASTERN AUSTRALIA ON THE BASIS OF DISCRIMINANT ANALYSIS

Group/Suite	No. of Samples	Predicted Group Membership					Percent Correctly Classified
		1	2	3	4	5	
1 Tamworth	11	11	0	0	0	0	100%
2 Hill End	29	20	2	3	1	3	69%
3 Hodgkinson	10	0	2	8	0	0	80%
4 Bendigo	7	0	0	0	7	0	100%
5 Cookman	8	0	2	0	0	6	75%

NOTE.—Total % of samples correctly classified = 81%.

arenite (Pettijohn 1963) were included. All averages were recalculated to 100% on a volatile-free basis in order to achieve a more meaningful comparison.

The most discriminating parameters are $Fe_2O_3^*$ + MgO%, TiO_2%, and the Al_2O_3/SiO_2, K_2O/Na_2O and $Al_2O_3/(CaO + Na_2O)$ ratios ($Fe_2O_3^*$ represents total iron as Fe_2O_3). Fe and Ti are useful because of their low mobility and low residence times in sea-water (Holland 1978). Although Mg has a high residence time in sea-water, it will remain unchanged in continental-margin type sandstones deposited by turbidites during burial because of the low permeability of these rocks (Blatt et al. 1980). The ratio Al_2O_3/SiO_2 gives an indication of the quartz enrichment in sandstones. The ratio K_2O/Na_2O is a measure of the K-feldspar and mica versus plagioclase content in the rock, and the $Al_2O_3/(CaO + Na_2O)$ parameter is a ratio of the most immobile to the most mobile elements. In general, there is a decrease in $Fe_2O_3^*$ + MgO, TiO_2, Al_2O_3/SiO_2 and an increase in K_2O/Na_2O and $Al_2O_3/(CaO + Na_2O)$ as the tectonic setting changes from oceanic island arc to continental island arc to active continental margins to the passive margin type (fig. 6).

Geochemical discriminant functions developed to distinguish the various sandstone suites of eastern Australia were used to assign tectonic settings to the published anal-

TABLE 5

AVERAGE CHEMICAL COMPOSITION OF SANDS AND SANDSTONES OF THE OCEANIC ISLAND ARC TECTONIC SETTING

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
SiO_2	59.20	57.56	59.22	62.00	58.49	58.0	57.34	66.19	63.45
TiO_2	.87	1.17	.93	...	1.41	.88	1.06	.60	.83
Al_2O_3	16.37	16.53	20.37	15.00	16.95	18.1	16.49	15.32	17.50
Fe_2O_3	1.73	1.74	2.68	7.7[a]	1.31	2.31	8.82[a]	8.69[a]	6.31[a]
FeO	5.02	7.69	2.62	...	7.70	4.6	...	...	...
MnO	.26	.17	.09	...	.13	.11	.14	.14	.12
MgO	2.74	3.9	2.91	3.8	4.06	3.28	4.87	4.80	2.70
CaO	7.62	5.28	6.53	6.7	3.67	5.93	5.14	5.06	2.67
Na_2O	4.78	5.05	2.42	3.8	4.60	4.00	4.13	4.07	4.88
K_2O	1.16	.70	1.91	1.4	1.67	2.58	1.75	1.72	1.33
P_2O_5	.18	.24	.31	...	.31	.22	.29	.29	.20
Fe_2O_3[a] + MgO	10.03	14.18	8.5	11.5	13.92	13.34	13.69	8.7	7.01
Al_2O_3/SiO_2	.28	.29	.34	.24	.29	.31	.29	.23	.28
K_2O/Na_2O	.24	.14	.78	.37	.36	.65	.42	.22	.23
$Al_2O_3/(Na_2O + CaO)$	1.30	1.60	2.28	1.43	2.05	1.82	1.77	1.91	2.31

NOTE.—All averages are recalculated on volatile free basis. (1) Tamworth suite, present work, (N = 11); (2) Baldwin Formation (Chappell 1968) (N = 10); (3) Napere graywacke, Aure Trough, Papua New Guinea (Edwards 1950) (N = 1); (4) Fore-arc sand (Maynard et al. 1980) (N = 9); (5) Volcanic graywacke, Taringatura, New Zealand (Coombs 1954) (N = 1); (6) Jurassic tuffaceous graywacke, Oregon (Dickinson) 1962) (N = 6); Central Sardinia graywacke, Italy (Ricci and Sabatini 1976) (N = 29); (8) Uyak Complex graywacke, Alaska (Connelly 1978) (N = 11); (9) Cape Current graywackes, Alaska (Connelly 1978) (N = 4); N = Number of Samples.

[a]Total iron as Fe_2O_3.

TABLE 6

AVERAGE CHEMICAL COMPOSITION OF SANDS AND SANDSTONES OF THE CONTINENTAL ISLAND ARC TECTONIC SETTING

	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)	(18)
SiO_2	74.38	69.0	71.5	66.6	72.92	70.1	73.5	69.63	68.69
TiO_2	.66	...	.6	.69	.61	.5	.6	.63	.83
Al_2O_3	12.25	14.0	14.7	15.9	12.29	14.0	14.8	14.09	14.41
Fe_2O_3	1.04	4.5[a]	1.0	2.2	5.73[a]	1.2	1.5	1.67	4.87[a]
FeO	2.96	...	2.6	3.1	...	3.1	2.9	3.65	...
MnO	.08	...	.1	.04	.11	.1	.1	.10	.10
MgO	1.49	2.4	1.2	2.8	1.72	2.3	1.6	2.19	2.07
CaO	2.66	4.4	1.9	3.0	2.49	2.5	1.0	2.61	3.52
Na_2O	2.52	3.6	3.6	3.0	3.15	3.7	2.5	3.02	3.00
K_2O	1.82	2.0	2.5	2.4	0.83	1.8	1.4	2.09	2.18
P_2O_5	.12	...	.2	.19	.17	.1	.1	.21	...
Fe_2O_3[a] + MgO	5.81	6.9	5.09	5.64	7.45	6.94	6.32	7.91	6.94
Al_2O_3/SiO_2	.16	.20	.21	.24	.17	.20	.20	.21	.21
K_2O/Na_2O	.72	.55	.69	.80	.26	.48	.56	.69	.73
$Al_2O_3/(Na_2O + CaO)$	2.36	1.75	2.67	2.65	2.18	2.28	3.79	2.76	2.21

NOTE.—All averages recalculated on volatile free basis. (10) Hill End suite, present work (N = 29); (11) Modern back-arc Sand (Maynard et al. 1982) (N = 27); (12) Alpine Facies, New Zealand (Reed 1957) (N = 14); (13) Middle Eocene Tyee graywackes, Oregon (Coleman 1972) (N = 3); (14) Kodiak Formation graywackes, Alaska (Connelly 1978) (N = 4); (15) Franciscan graywackes, California (Bailey et al. 1964) (N = 21); (16) Culm graywackes, Harz Mountains (Huckenholz 1963) (N = 20); (17) Average graywacke (Pettijohn 1963) (N = 61); (18) Average Columbia river sand (Whetten et al. 1969) (N = 68); N = Number of samples.

[a]Total iron as Fe_2O_3.

yses of sands and sandstones (tables 5–8). Discriminant scores for averages of the published analyses were calculated using the unstandardized function coefficient of table 3 and the actual abundance of element oxide in the average. The results, given in table 9 and plotted on the territorial map obtained from the eastern Australia data (fig. 7), show that 90% of the suites are correctly classified to their expected tectonic settings.

The oceanic island arc sandstones are most distinctive and are characterized by high $Fe_2O_3^*$ + MgO (8 to 14%); high TiO_2 (0.8 to 1.4%); high Al_2O_3/SiO_2 (0.24 to 0.33); low

TABLE 7

AVERAGE CHEMICAL COMPOSITION OF SANDS AND SANDSTONES OF THE ACTIVE CONTINENTAL MARGIN TYPE TECTONIC SETTING

	(19)	(20)	(21)	(22)	(23)	(24)	(25)
SiO_2	78.55	69.0	71.98	71.66	72.72	80.18	72.96
TiO_2	.45	...	.45	.39	.66	.31	.51
Al_2O_3	11.08	15.0	13.27	14.13	12.97	9.04	14.76
Fe_2O_3	.64	4.1[a]	1.84	1.75	5.12[a]	1.56	.73
FeO	2.00	...	1.71	1.17	...	.73	2.32
MnO	.05	...	.06	.05	.08	.28	0.05
MgO	.93	1.9	1.79	1.24	1.55	.52	.69
CaO	1.19	4.2	2.76	3.17	1.65	2.81	1.59
Na_2O	2.32	3.8	3.17	3.05	2.84	1.56	2.62
K_2O	2.71	2.6	2.84	3.28	2.27	2.91	3.67
P_2O_5	.08	...	.14	.06	...	.1	.03
Fe_2O_3[a] + MgO	3.79	6.0	5.5	4.2	6.67	2.89	3.99
Al_2O_3/SiO_2	.14	.22	.18	.20	.18	.11	.21
K_2O/Na_2O	1.17	.68	.89	1.08	.80	1.86	1.40
$Al_2O_3/(Na_2O + CaO)$	3.15	1.88	2.23	2.27	2.88	2.07	3.51

NOTE.—All averages recalculated on volatile free basis. (19) Hodgkinson suite, present work (N = 10); (20) Modern Leading Edge sand (Maynard et al. 1982) (N = 15); (21) Eocene-Oligocene sandstones, Santa Ynez, California (Van de Kamp et al. 1976) (N = 26); (22) Holocene sand, Salton Basin, California (Van de Kamp et al. 1976) (N = 6); (23) Rensselaer graywacke, New York (Ondrick and Griffiths 1969) (N = 119); (24) Average Arkose (Pettijohn 1963) (N = 32); (25) Modern rhyolite sand (Webb and Potter 1969) (N = 4); N = Number of samples.

[a]Total iron as FeO_3.

TABLE 8

AVERAGE CHEMICAL COMPOSITION OF SANDS AND SANDSTONES OF THE PASSIVE MARGIN TECTONIC SETTING

	(26)	(27)	(28)	(29)	(30)	(31)	(32)	(33)	(34)
SiO_2	85.69	87.80	78.0	88.82	74.23	86.25	72.90	96.60	71.50
TiO_2	.50	.28	...	.39	.69	.76	.33	.20	1.21
Al_2O_3	7.53	8.07	9.8	5.88	12.55	6.17	8.93	1.10	13.40
Fe_2O_3	.56	.54	2.9[a]	.39	.91	1.52[a]	4.19	.40	1.30
FeO	1.63	.49	...	1.35	3.79	...	1.54	.20	3.60
MnO	.02	.03	...	.02	.06	...	.11	...	.10
MgO	1.01	.40	1.3	.83	2.39	1.17	2.65	.10	1.00
CaO	.19	.10	4.1	.39	.90	1.07	6.84	1.60	1.00
Na_2O	1.39	.91	1.9	.69	1.51	1.03	.99	.10	2.80
K_2O	1.33	1.30	2.0	1.18	2.76	1.99	1.43	.20	1.60
P_2O_5	.13	.08	...	.09	.20	.08	.11	...	.14
Fe_2O_3[a] + MgO	3.38	1.48	4.2	2.72	7.51	2.69	8.55	0.62	6.30
Al_2O_3/SiO_2	.09	.09	.13	.07	.17	.08	.12	.001	.19
K_2O/Na_2O	.96	1.42	1.2	1.71	1.82	1.93	1.44	2.0	.57
$Al_2O_3/(Na_2O + CaO)$	4.76	7.99	1.6	5.4	5.23	2.93	1.14	.64	3.52

Note.—All averages recalculated on volatile free basis. (26) Bendigo suite, present work (N = 7); (27) Cookman suite, present work (N = 7); (28) Modern Trailing Edge sand (Maynard et al. 1982) (N = 29); (29) Quartz-rich graywacke, mainly from Tasman Geosyncline (Crook 1974) (N = 24); (30) Greenland Graywacke, New Zealand (Nathan 1976) (N = 6); (31) Cambrian-Quaternary sand, North American platform (Ronov and Migdisov 1971); (32) Average Lithic-Arenite (Pettijohn 1963) (N = 20); (33) Average Quartz-Arenite (Pettijohn 1963) (N = 26); (34) Greenish-grey Charny Sandstone, Canada (Middleton 1972) (N = 4); N = Number of samples.

[a]Total iron as Fe_2O_3.

K_2O/Na_2O (0.2 to 0.4); and low $Al_2O_3/(CaO + Na_2O)$ (1 to 2) (fig. 6). Examples of sands and sandstones of this tectonic setting are common in the Circum-Pacific region. These sandstones plot in the field of the Tamworth suite on the discriminant function plot (fig. 7); thus this field is characteristic of the oceanic island arc type setting. The modern fore-arc sands are geochemically similar to other sandstones of this tectonic setting.

Continental island arc sandstones are discriminated from the oceanic island arc type by their lower $Fe_2O_3^* + MgO$ (5 to 8%); lower TiO_2 (0.5 to 0.7%); lower Al_2O_3/SiO_2 (0.15 to 0.20); higher K_2O/Na_2O (0.4 to 0.8); and higher $Al_2O_3/(CaO + Na_2O)$ (0.5 to 2.5) (fig. 6). Examples of sands and sandstones of this tectonic setting are also common in the Circum-Pacific region (table 6). Deep-sea sands of the back-arc region are assigned to this category on the basis of similar geochemical characteristics. These sands and sandstones are derived from a wide range of sources but have a dominant contribution from felsic volcanic rocks. They fall in the field occupied by the Hill End suite samples on the discriminant function plot (fig. 7). Thus, this field is characteristic of the continental island arc type of sandstones.

Sandstones of the active continental margin type tectonic setting can be discriminated from those of the continental island arc by their lower $Fe_2O_3^* + MgO$ (2 to 5%); lower TiO_2 (0.25 to 0.45%); lower Al_2O_3/SiO_2 (0.1 to 0.2); and higher K_2O/Na_2O (fig. 6). These sandstones are mainly derived from granite-gneisses and siliceous volcanics. The modern deep-sea sands of the leading edge are similar in geochemical characteristics to sandstones of this category except for having slightly higher Al_2O_3/SiO_2 and lower K_2O/Na_2O ratios. The average arkose has geochemical characteristics similar to sandstones of this class, except for having higher K_2O/Na_2O and lower Al_2O_3/SiO_2 ratios. Most of the sandstone suites listed in table 8 plot in the field of the Hodgkinson suite sandstones on the discriminant function plot (fig. 7). This field is characteristic of the active continental margin type sandstones. The Santa Ynez arkoses of California are mainly derived from granites and gneisses of the uplifted basement provenance (Van de Kamp et al. 1976; Dickinson and Suczek 1979) and can be assigned to the Andean type active continental margin, as also shown by geochemical parameters (fig. 6). However, on the basis of discriminant functions, they are assigned to the continental island arc type of setting. It has been suggested that the volcanics present in the

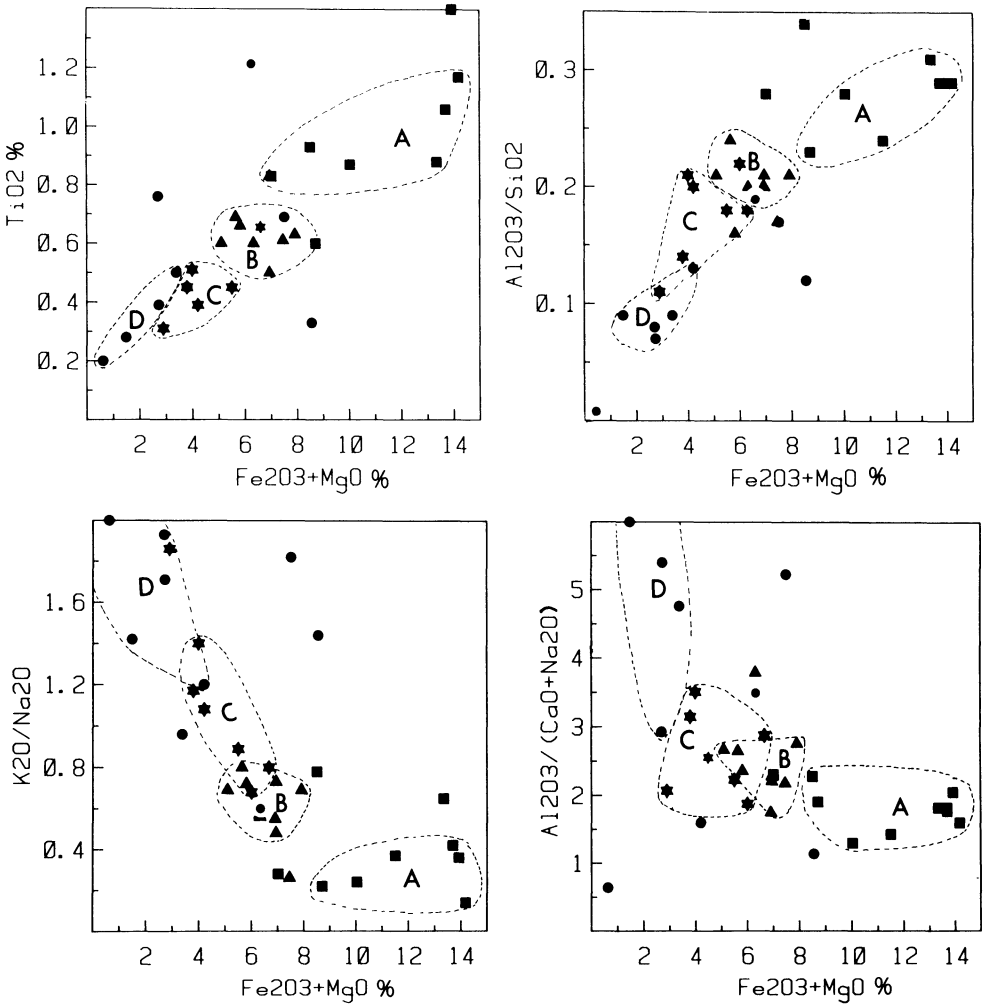

FIG. 6.—Major element composition plots of sands and sandstones for tectonic setting discrimination. Plot of TiO_2, Al_2O_3/SiO_2, K_2O/Na_2O, and $Al_2O_3/(CaO + Na_2O)$ versus $Fe_2O_3 + MgO$. (Fe_2O_3 represents total iron as Fe_2O_3). Data from tables 5–8. Dotted lines mark the major fields of sandstones representing various tectonic settings, though some points fall outside these fields. Fields and symbols are: A—Oceanic island arc *(squares);* B—Continental island arc *(triangles);* C—Active continental margin *(stars);* D—Passive margins *(circles).*

source region were preferentially lost in solution during the Santa Ynez sedimentation (Van de Kamp et al. 1976). This volcanic component, which is otherwise difficult to detect, probably causes these sandstones to fall in the continental island arc field.

Sands and sandstones of the passive margins exhibit a large variation in their compositions, especially in the K_2O/Na_2O and $Al_2O_3/(CaO + Na_2O)$ ratios (table 8). Their characteristics overlap slightly with those of active margin sandstones, but they can be discriminated by their lower $Fe_2O_3^* + MgO$, Al_2O_3/SiO_2 and higher K_2O/Na_2O and $Al_2O_3/(CaO + Na_2O)$ ratios (fig. 6). These features indicate their highly recycled nature with the enrichment of quartz and the depletion of chemically unstable grains, e.g., feldspars. The Ordovician graywackes of the Greenland Group, New Zealand, are significantly high in $Fe_2O_3^* + MgO$, TiO_2, and the Al_2O_3/SiO_2 ratio. However, their K_2O/Na_2O and $Al_2O_3/(CaO + Na_2O)$ ratios are typical of sandstones of this class. Modern deep sea sands of the trailing margins have geochemical characteristics similar to sandstones of this class, except for being lower in $Al_2O_3/(CaO + Na_2O)$ ratio, probably due to the presence

TABLE 9

TECTONIC SETTING CLASSIFICATION OF VARIOUS SANDSTONE SUITES ON THE BASIS OF DISCRIMINANT ANALYSIS

Expected Tectonic Setting	Discriminant Scores	
	Function I	Function II
Oceanic Island Arc		
Tamworth Suite	3.22	.53
Baldwin Formation	4.12	.62
Aure Trough, PNG	1.98	3.70
Modern Fore-arc Sand	2.62	−1.50
Taringatura, New Zealand	4.04	.79
Jurassic Oregon	3.32	1.42
Sardinia Italy	3.36	.97
Uyak Complex, Alaska	2.01	−1.07
Cape Current, Alaska	2.66	−.30
Continental Island Arc		
Hill End Suite	−.13	−.35
Modern Back-Arc Sand	1.40	−1.98
Alpine Facies, New Zealand	1.14	−.66
Tyee, Oregon	1.20	−1.38
Kodiak, Alaska	.78	−.14
Franciscan, California	.96	.55
Harz, Germany	−.12	.92
Average Graywacke	1.14	.17
Columbia River Sand	.40	.05
Active Continental Margin		
Hodgkinson Suite	−.88	−1.89
Modern Leading Edge Sand	1.47	−4.91
Santa Ynez, California[a]	.48	−.57
Salton Basin Sand, California	−.20	−3.00
Rensselaer, New York	1.01	−5.35
Average Arkose	−1.90	−.98
Modern Ryolitic Sand	−.76	−4.21
Passive Margin		
Bendigo Suite	−1.65	1.58
Quartz-rich Graywacke	−2.56	.26
Modern Trailing Edge Sand[b]	−.13	−2.98
Cookman Suite	−2.67	.20
Greenland, New Zealand	−1.57	2.27
Cambrian-Quaternary Sand	−1.25	2.58
Av. Lithic Arenite	−1.01	2.67
Charny Sandstone, Quebec[a]	−.52	.13
Av. Quartz Arenite	−3.21	1.64

NOTE.—All sandstone suites are assigned to the expected tectonic setting, except those marked, which are assigned to the following tectonic settings:
[a]Continental island arc.
[b]Active Continental margin.

of biogenic carbonates. The average lithic arenite (Pettijohn 1963) has geochemical characteristics quite similar to sandstones of this tectonic setting, except for having a higher MgO and CaO content. The average Cambrian-Quaternary sand of the North American platform (Ronov and Migdisov 1971) is also similar in composition to the sandstones of this tectonic setting, except for being higher in TiO_2 and CaO.

The Cambrian Charny Sandstone of Quebec, which was deposited on a passive continental margin, has some characteristics, such as $Fe_2O_3^* + MgO$ and the Al_2O/SiO_2 and $Al_2O_3/(CaO + Na_2O)$ ratios, similar to the sands and sandstones of the continental island arc setting. Granites and gneisses of the Canadian shield have been inferred to form the source rocks of these sediments (Middleton 1972). The high TiO_2 and $Fe_2O_3^* + MgO$ contents of these sandstones indicate significant contribution from volcanic sources, and probably causes the grouping of these samples with the continental island arc sand-

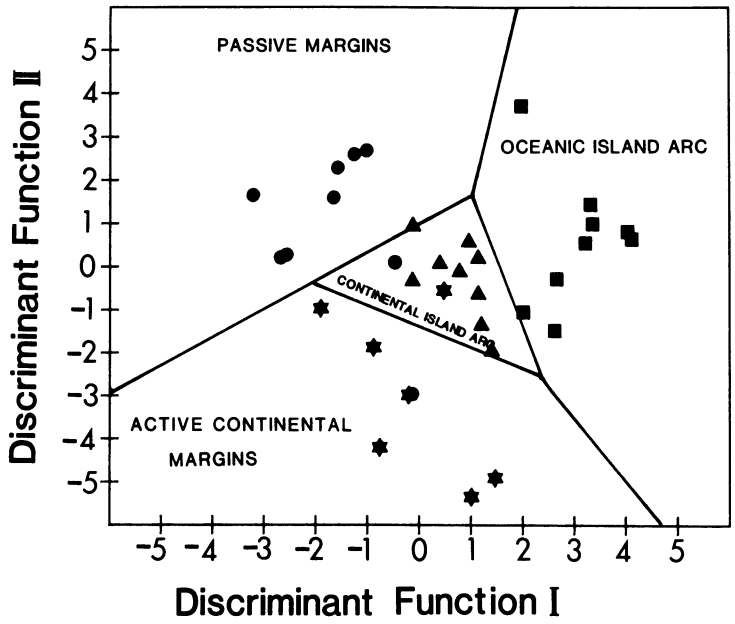

FIG. 7.—Plot of discriminant scores along Function I versus II for various sands and sandstones given in tables 5–8 (values of calculated discriminant scores are given in table 9). Note the excellent discrimination of various tectonic settings. The territorial map is based on data of Paleozoic suites of eastern Australia and adopted from figure 5. Symbols as in figure 6.

stones (figs. 6 and 7). This volcanic component may have been derived from the continental shield or from intra-cratonic volcanic rocks which may have erupted during the rift-valley or graben stages, before the formation of the passive margin.

Most of the other suites of table 8 fall in the field of the Bendigo and Cookman suites on the discriminant function plot (fig. 7). This territory characterizes the passive continental margins. However, modern deep sea sands of the trailing margins plot in the active continental margin field. This is attributed to the high CaO content probably of biogenic affinity in modern sands *and suggests that there may be some differences in the characteristics of modern and ancient sandstones within one tectonic setting.*

AVERAGE COMPOSITIONS OF SANDSTONES

Sandstones exhibit a large variation in their bulk composition. The average major element compositions of various sandstone types have been computed based on mineralogy, e.g., arkose, graywacke, etc. (Pettijohn 1963) and on tectonic settings (Middleton 1960). These estimates are based on a very old data set. A large number of good quality analyses of sands and sandstones have become available in the literature in recent years. As tectonism is the primary control on sandstone composition, the average compositions of sandstones of various tectonic settings, along with some estimate of uncertainty (standard deviations), are computed (table 10). The trace element averages for sandstones of the various tectonic settings are given in Bhatia and Crook (1983).

The average composition of the oceanic island arc sandstones is similar to that of average andesite or total crust (cf. Taylor 1979; Ewart 1976). The average composition of sandstones of the continental island arc tectonic setting is similar to that of "continental" or "quasi-continental" calc-alkaline rocks (cf. Johnson et al. 1978; Bailey 1981). The average composition of active continental margin type sandstones is characterized by equal amounts of K_2O and Na_2O and the bulk composition is similar to that of the crystalline basement of the upper continental crust (cf. Taylor 1979). Passive margin type sandstones are characterized by a high abundance of SiO_2 and low abundances of Na_2O,

TABLE 10

AVERAGE CHEMICAL COMPOSITION OF SANDSTONES OF VARIOUS TECTONIC SETTINGS

	Oceanic Island Arc[a]		Continental Island Arc[b]		Active Continental Margin[c]		Passive Margin[d]	
	$\bar{X}$	±sd	$\bar{X}$	±sd	$\bar{X}$	±sd	$\bar{X}$	±sd
SiO_2	58.83	1.6	70.69	2.6	73.86	4.0	81.95	6.2
TiO_2	1.06	.2	.64	.1	.46	.1	.49	.2
Al_2O_3	17.11	1.7	14.04	1.1	12.89	2.1	8.41	2.2
Fe_2O_3	1.95	.5	1.43	.5	1.30	.5	1.32	1.6
FeO	5.52	2.1	3.05	.4	1.58	.9	1.76	1.2
MnO	.15	...	.10	...	.10	...	.05	...
MgO	3.65	.7	1.97	.5	1.23	.5	1.39	.8
CaO	5.83	1.3	2.68	.9	2.48	1.0	1.89	2.3
Na_2O	4.10	.8	3.12	.4	2.77	.7	1.07	.6
K_2O	1.60	.6	1.89	.5	2.90	.5	1.71	.6
P_2O_5	.26	.1	.16	.1	.09	...	.12	...
Fe_2O_3[g] + MgO	11.73		6.79		4.63		2.89[e]	
Al_2O_3/SiO_2	.29		.20		.18		.10	
K_2O/Na_2O	.39		.61		.99		1.60	
$Al_2O_3/(CaO + Na_2O)$	1.72		2.42		2.56		4.15[f]	

NOTE.—All averages ($\bar{X}$) on volatile free basis. Uncertainties (sd) represent 1 standard deviation.
[a]Unweighted average of 1–7 of table 5.
[b]Unweighted average of 10–18 of table 6.
[c]Unweighted average of 19–25 of table 7.
[d]Unweighted average of 26–32 of table 8.
[e]Typical value—calculated without 30 & 32 of table 8.
[f]Typical value—average of individual ratios from table 8.
[g]Total iron as Fe_2O_3.

CaO, and TiO_2. This composition is similar to the average composition of the sedimentary cover of the Russian and North American platforms (cf. Ronov and Migdisov 1971).

CONCLUSIONS

The major element geochemistry of sandstones can be used to infer the provenance type and the plate tectonic setting of ancient sedimentary basins. The optimum discrimination of sandstones representing the various tectonic settings is achieved by the plots of $Fe_2O_3^*$ + MgO versus TiO_2, Al_2O_3/SiO_2, K_2O/Na_2O, and $Al_2O_3/(CaO + Na_2O)$. The oceanic island arc sandstones dominantly derived from calc-alkaline andesites are characterized by a higher abundance of TiO, Al_2O_3, Na_2O, and Fe_2O_3 and a lower abundance of SiO_2 and K_2O compared to all other sandstones. The continental island arc sandstones, dominantly derived from felsic volcanic rocks, are characterized by higher SiO_2, K_2O, and the K_2O/Na_2O ratio ($\simeq$ 0.6) and lower $Fe_2O_3^*$ + MgO than the oceanic island arc sandstones. The active continental margin (Andean type and strike-slip basins) sandstones are dominantly derived from the uplifted basement and reflect the composition of the upper continental crust in their higher SiO_2 and K_2O content and $K_2O/Na_2O \simeq 1$. The passive margin type sandstones show a large variation in their characteristics, which sometimes overlap with those of the active continental margins. They are generally significantly enriched in SiO_2 and depleted in Al_2O_3, TiO_2, Na_2O, and CaO and have a K_2O/Na_2O ratio of more than 1.

ACKNOWLEDGMENTS.—I am grateful to Keith Crook for his suggestions and for going through the manuscript critically and to Bruce Chappell for his help with the geochemical analyses. Ross Freeman, Jack Wasik, and Jack Pennington gave technical assistance in the geochemical analyses. Paul Edwin Potter and Raymond Siever provided helpful reviews.

REFERENCES CITED

BAILEY, E. H.; IRWIN, W. P.; and JONES, D. L., 1964, Franciscan and related rocks and their significance in the geology of western California: California Div. Mines Geol. Bull. 183, 177 p.

BAILEY, J. C., 1981, Geochemical criteria for a refined tectonic discrimination of orogenic andesites: Chem. Geol., v. 32, p. 139–154.

BHATIA, M. R., 1981, Petrology, geochemistry, and tectonic setting of some flysch deposits: Unpub. Ph.D. thesis, Australian National University, Canberra, 382 p.

——— 1983, Rare-earth element geochemistry in the provenance type and tectonic setting determination of sedimentary rocks: Sedimentology, in Press.

———, and CROOK, K. A. W., 1983, Trace element characteristics of greywackes and the tectonic setting discrimination of sedimentary basins: in prep.

———, and TAYLOR, S. R., 1981, Trace element geochemistry and sedimentary provinces: a study from the Tasman Geosyncline, Australia: Chem. Geol., v. 33, p. 115–125.

BLATT, H.; MIDDLETON, G. V.; and MURRAY, R., 1980, Origin of Sedimentary Rocks: Englewood Cliffs, NJ, Prentice-Hall, 782 p.

CHAPPELL, B. W., 1968, Volcanic graywackes from the Upper Devonian Baldwin Formation, Tamworth-Barraba district, N.S.W: Jour. Geol. Soc. Australia, v. 15, p. 87–102.

COLEMAN, R. G., 1972, The Colebroke Schist of Southwestern Oregon and its relation to the tectonic evolution of the region: U.S. Geol. Surv. Bull. 1339, 61 p.

CONNELLY, W., 1978, Uyak Complex, Kodiak Island, Alaska: a Cretaceous subduction complex: Geol. Soc. America Bull., v. 89, p. 755–769.

COOLEY, W. W., and LOHNES, P. R., 1971, Multivariate Data Analyses: New York, Wiley, 364 p.

COOMBS, D. S., 1954, The nature and alteration of some Triassic sediments from Southland New Zealand: Roy. Soc. New Zealand Trans., v. 82, p. 65–109.

COOPER, J. A., 1963, The flame photometric determination of potassium in geological materials used for potassium-argon dating: Geochim. Cosmochim. Acta, v. 27, p. 527–546.

CROOK, K. A. W., 1974, Lithogenesis and geotectonics: the significance of compositional variations in flysch arenites (graywackes), *in* DOTT, R. H., and SHAVER, R. H., eds., Modern and ancient geosynclinal sedimentation: SEPM Spec. Pub. 19, p. 304–310.

CUMMINS, W. A., 1962, The graywacke problem: Geol. Jour., v. 3, p. 51–72.

DAVIES, D. K., and ETHRIDGE, F. G., 1975, Sandstone composition and depositional environments: Am. Assoc. Petrol. Geol. Bull., v. 59, p. 239–264.

DAVIS, J. C., 1973, Statistics and Data analyses in Geology: New York, Wiley, 550 p.

DICKINSON, W. R., 1962, Petrology and diagenesis of Jurassic andesitic strata in Central Oregon: Am. Jour. Sci., v. 260, p. 481–500.

——— 1974, Plate tectonics and sedimentation, *in* DICKINSON, W. R., ed., Tectonics and sedimentation: SEPM Spec. Pub. 22, p. 1–27.

———, and SEELY, D. R., 1979, Structure and stratigraphy of forearc regions: Am. Assoc. Petrol. Geol. Bull., v. 63, p. 2–31.

———, and SUCZEK, C. A., 1979, Plate tectonics and sandstone compositions: Am. Assoc. Petrol. Geol. Bull., v. 63, p. 2164–2182.

———, and VALLONI, R., 1980, Plate settings and provenance of sands in modern ocean basins: Geology, v. 8, p. 82–86.

EDWARDS, A. B., 1950, The petrology of the Miocene sediments of the Aure Trough, Papua: Proc. Roy. Soc. Victoria, v. 60, p. 123–148.

EWART, A., 1976, Mineralogy and chemistry of modern orogenic lavas—some statistics and implications: Earth Planet. Sci. Letters, v. 31, p. 417–432.

HAWKINS, J. W., JR., and WHETTEN, J. T., 1969, Graywacke matrix minerals: hydrothermal reactions with Columbia River sediments: Science, v. 66, p. 868–870.

HÜCKENHOLZ, H. G., 1963, Mineral composition and texture in graywackes from the Harz Mountains (Germany) and in arkoses from the Auvergne (France): Jour. Sed. Petrol., v. 33, p. 914–918.

JOHNSON, R. W.; MACKENZIE, D. E.; and SMITH, I. E. M., 1978, Volcanic rock associations at convergent plate boundaries: reappraisal of the concept using case histories from Papua-New Guinea: Geol. Soc. America Bull., v. 89, p. 96–106.

KAY, M., 1951, North American geosynclines: Geol. Soc. America Mem. 48, 143 p.

KLOVAN, J. E., and BILLINGS, G. K., 1967, Classification of geological samples by discriminant-function analysis: Can. Petrol. Geol. Bull., v. 15, p. 313–330.

LE MAITRE, R. W., 1976, The chemical variability of some common igneous rocks: Jour. Petrology, v. 17, p. 589–637.

——— 1982, Numerical Petrology: Statistical Interpretation of Geochemical Data; Amsterdam, Elsevier, 281 p.

MAYNARD, J. B.; VALLONI, R.; and YU, H., 1982, Composition of modern deep sea sands from arc-related basins: Geol. Soc. London Spec. Pub. 10, p. 551–561.

MIDDLETON, G. V., 1960, Chemical composition of sandstone: Geol. Soc. America Bull., v. 71, p. 1011–1026.

——— 1962, A multivariate statistical technique applied to the study of sandstone composition: Roy. Soc. Canada Trans., Ser. III, no. 106, p. 119–126.

——— 1972, Albite of secondary origin in Charny sandstones, Quebec: Jour. Sed. Petrol., v. 42, p. 341–349.

MITCHELL, A. H. G., and READING, H. G., 1969, Continental margins, geosynclines, and ocean floor spreading: Jour. Geology, v. 77, p. 629–646.

NATHAN, S., 1977, Geochemistry of the Greenland Group (Early Ordovician), New Zealand: New Zealand Jour. Geol. Geophys., v. 19, p. 683–706.

NIE, N. H.; HULL, C. H.; JENKINS, J. G.; STEINBRENNER, K.; and BENT, D. M., 1975, SPSS statistical package for the social sciences: New York, McGraw-Hill, 675 p.

NORRISH, K., and HUTTON, J. T., 1969, An accurate X-ray spectrographic method for the analysis of a wide range of geological samples: Geochim. Cosmochim. Acta, v. 33, p. 431–454.

ONDRICK, C. W., and GRIFFITHS, J. C., 1969, Frequency distribution of elements in Rensselaer graywacke, Troy, New York: Geol. Soc. America Bull., v. 80, p. 509–518.

PECK, L. C., 1964, Systematic analysis of silicates: U.S. Geol. Surv. Bull. 1170, 89 p.

PETTIJOHN, F. J., 1963, Chemical composition of sandstones, excluding carbonate and volcanic sands, *in* FLEISCHER, M., ed., Data of geochemistry: U.S. Geol. Surv. Prof. Paper 440-S, 19 p.

———; POTTER, P. E.; and SIEVER, R., 1972, Sand and Sandstone: New York, Springer-Verlag, 618 p.

POTTER, P. E., 1978, Petrology and chemistry of modern big river sands: Jour. Geology, v. 86, p. 423–449.

READ, J. J., 1957, Petrology of the Lower Mesozoic rocks of the Wellington district: Geol. Surv. New Zealand Bull. 57, p. 9–60.

RICCI, C. A., and SABATINI, G., 1976, An example of sedimentary differentiation in volcano-sedimentary series; the high chromium metagraywackes of Central Sardinia (Italy): N. Jb. Miner. Mh., heft 7, p. 307–319.

RONOV, A. B., and MIGDISOV, A. A., 1971, Geochemical history of the crystalline basement and the sedimentary cover of the Russian and North American platform: Sedimentology, v. 16, p. 137–185.

SCHWAB, F. L., 1975, Framework mineralogy and chemical composition of continental margin-type sandstone: Geology, v. 3, p. 487–490.

SIEVER, R., 1979, Plate-tectonic controls on diagenesis: Jour. Geology, v. 87, p. 127–155.

TAYLOR, S. R., 1979, Chemical composition and evolution of the continental crust: the rare earth element evidence, *in* MCELLINNEY, M. W., ed., The Earth: Its Origin, Structure, and Evolution: New York, Academic Press, p. 353–376.

VALLONI, R., and MAYNARD, J. B., 1981, Detrital modes of recent deep-sea sands and their relation to tectonic setting: a first approximation: Sedimentology, v. 28, p. 75–83.

VAN DE KAMP, P. C.; LEAKE, B. E.; and SENIOR, A., 1976, The petrography and geochemistry of some Californian arkoses with application to identifying gneisses of metasedimentary origin: Jour. Geology, v. 84, p. 195–212.

WEBB, W. M., and POTTER, P. E., 1969, Petrology and chemical composition of modern detritus derived from rhyolitic terrain, western Chihuahua: Soc. Geol. Mexicana Bol., v. 32, p. 45–61.

WHETTEN, J. T.; KELLEY, J. C.; and HANSON, L. G., 1969, Characteristics of Columbia River sediment transport: Jour. Sed. Petrol., v. 39, p. 1149–1166.